Hybrid robotic system for applications in robotic surgery

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Abstract—**In this paper a design of a hybrid robotic system intended for use in laparoscopic and key-hole surgery is presented. The hybrid robotic system consists of a pneumatically driven continuum robot serially attached to a rigid robotic arm. Pneumatic actuation allows for inherent flexibility of the continuum robot which can contribute to the overall level of safety of the robotic surgery.**

I. Introduction

Continuum robots are considered more and more for use in surgical interventions. Their ability to bend and flex upon contact with the environment is considered extremely appealing especially from a safety point of view. When compared to their rigid counterparts such as the Intuitive Surgical Da Vinci system, the compliance many of the continuum robots exhibit makes it easier to keep force levels down. Here, the pneumatically driven robots can be particularly appealing due to their inherently compliant nature [2], [5].

The access port for surgical instruments resulting from the MIS approach particularly limits the dexterity of the surgical instruments, hence additional degrees of freedom are required to correctly position and align the instruments. For example, in transapical approach to TAVI [3], the flexible instrument (catheter) is inserted into the heart in the apex area through the access port (trocar). By introducing the instrument through the trocar, the surgeon is effectively losing two degrees of freedom. Her/his motions are restricted to insertion /retraction, rotation and pivoting about the entry point. By using an instrument which offers two additional local DoFs past the trocar point, instrument dexterity can be restored, allowing for complete control over position and orientation of the tool. A combination of a rigid robot with a tip-mounted active continuum robot would restore the 6 DoFs required to correctly position and align the surgical instruments.

Figure 1 illustrates conceptually how such system could be used for example for a robot-assisted transapical, transcatheter aortic valve implantation. The prosthetic valve would be mounted here on top of the flexible surgical instrument. In more challenging procedures such as mitral valve repair and mitral valve replacement such robotic approach could bring even more benefits. The remainder of the paper is organised as follows: first the design of the pneumatically driven continuum robot is shown in Section II. The hybrid robot is introduced in Section III.

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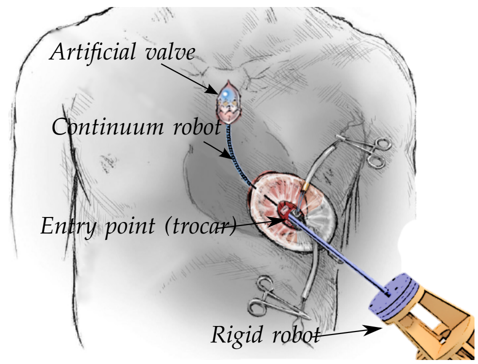


Figure 1: Illustration of an exemplary robot-assisted heart procedure. In trans-catheter transapical aortic valve implantation the native valve has to be replaced by a prosthetic valve which could be mounted on a dynamically controlled hybrid robotic system as illustrated here.

II. Continuum robot design

The continuum robot, depicted in Fig. 2, is a composite structure actuated with four McKibben muscles (a type of pneumatic artificial muscles, PAM) embedded into a flexible nitinol (NiTi) tube. In order to achieve the desired maximal bending and stiffness, the tube has been cut using wire-EDM, as shown in Fig. 2. The resulting structure is 66 mm long and has an external diameter of 7 mm. Each muscle is 65 mm long, has an initial diameter of 2.1 mm, and it is fastened at each side of the continuum robot.

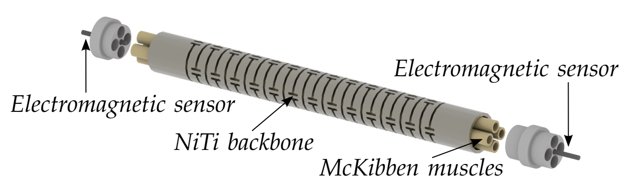


Figure 2: The robot is built from a NiTi tube designed to achieve the desired bending. Four McKibben muscles are embedded inside the NiTi tube. At the connection pieces at the tip and the rear two electromagnetic tracking sensors are attached.

The actuation is realised pneumatically. An increase of pressure induces a radial expansion of the muscle, as well as an axial contraction, and thereby an axial pulling force. This pulling force is applied to the structure, making it bend. Characterized by a high power

Figure 3: The experimental set-up and the corresponding close-up picture of the continuum robot.

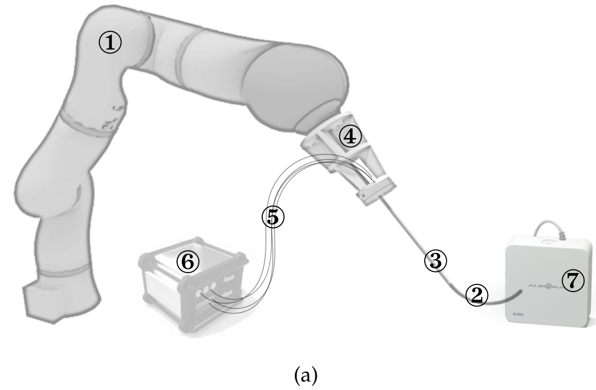


Figure 4: Hybrid robotic system consisting of a flexible continuum robot mounted on a rigid robot arm (a). The rigid robot provides 7 DoFs and two additional DoFs are offered by the continuum robot (b).

density, McKibben muscles are also inherently more compliant than other actuation principles. An extensive characterization of artificial muscles can be found in the literature [4], [6], [7].

Note that the surrounding NiTi tube acts as a return spring, so that the continuum robot straightens back if the pressure is released. The four muscles are symmetrically distributed within the NiTi tube, so that bending motions in two directions are achieved by pressurizing one or more artificial muscles.

The maximum bending curvature of the structure is defined by the composite stiffness of both the muscles and of the NiTi tube, as well as the pressure to force ratio of the artificial muscles. The relation between the curvature of the continuum robot to the applied pressure can then be expressed with a parameter K which has a unit of [$1/\mathrm{Pa}\cdot\mathrm{mm}$]. This parameter was obtained experimentally by linearly increasing the pressure in one of the muscles and measuring the bending angle using the embedded electromagnetic sensors. The obtained value for this parameter is $K = 0.0143[1/\mathrm{Pa}\cdot\mathrm{mm}]$.

Two electromagnetic (*em*) tracking sensors (NDI, Aurora) are embedded at both extremities of the continuum robot. These *em*-sensors allow measurement of the relative pose of the tip of the continuum robot with respect to its base. An interrogator module is placed in the vicinity of the site of interest, giving absolute position measurements (with respect to the interrogator's coordinate frame) of the continuum robot.

III. Hybrid robot

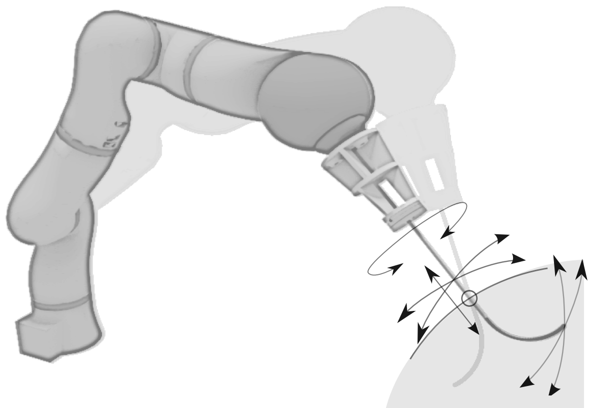
Fig. 4a shows the proposed hybrid-robotic system. The hybrid robot employed in this work consists out of a pneumatically actuated continuum robot ② mounted on a longer shaft ③ which is used to pass the surgical tool through a trocar. This shaft is rigidly connected to a 3D-printed mounting stage ④ which is finally mounted on the rigid robot ①. The rigid robot employed in this study is a KUKA LWR robot featuring 7 DoF. The continuum robot control box ⑥ contains four valves (SMC ITV-0050) to supply the pressure to the continuum robot through the long pressure tubes ⑤. The servo-valve uses an internal pressure controller that regulates the pressure with 0.01 bar accuracy.

An electromagnetic field generator module (NDI, Aurora) ⑦ is placed in the vicinity of the site of interest, giving absolute position measurements (with respect to the coordinate frame of the field generator) of the tip and base of the continuum robot.

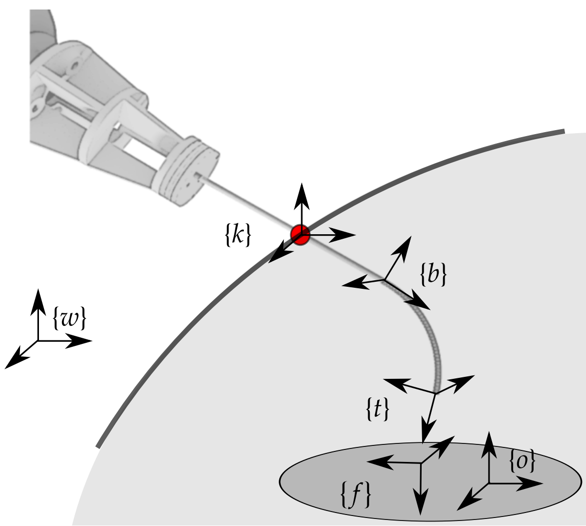
The overall DoFs of the combined rigid and continuum robot are indicated on Fig. 4b. The discrete joints $q_1 ... q_7$ are rotational joints provided by the KUKA LWR robot. Continuum robot joints are q_{cc_1} and q_{cc_2}.

Control

For control, a quadratic programming framework (eTC, descibed in [1]) was employed. The robot is here controlled at the velocity level by utilizing the differential kinematics of the robot. The framework allows for a user-friendly definition of multiple tasks which are imposed as constraint on the robot controller. Constraints are defined as equalities and inequalities,



(a)



(b)

Figure 5: Motions of the robot under the trocar constraint (a) and representation of the scene and the frames which define the relation between the objects in the scene (b).

Table I: Different control goals.

Constraint	Constraint importance	Constraint type
tip position	S	=
tip orientation	S	=
entry point	S	=
joint velocity limit	H	≤
joint position limit	H	≤
pressure limit	H	≤

whose levels of importance (hard and soft) by means of weights. In case of conflicting task objectives, the robot controller makes use of such weights in order to find a trade-off between achieving such constraints. Table I contains a set of different position constraints used to demonstrate the control of the robot.

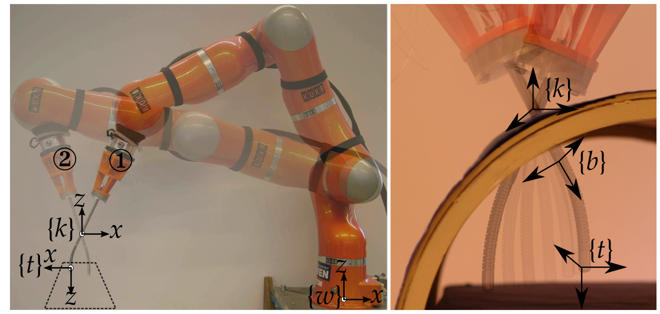


Figure 6: The working principle and motions of the developed hybrid robotic system.

IV. Conclusion

This paper proposes a hybrid robotic and control approach, combining a classical rigid robot with a continuum segment, in order to overcome the classical limitations of keyhole surgery. The rigid robot allows 6-DoF instrument positioning while the continuum robot adds two more DoF at the tip, effectively restoring the 2 DoFs that are lost when passing through a trocar. The continuum robot tip is compliant and as such introduces extra safety into the system, reducing the risk for tissue damage.

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